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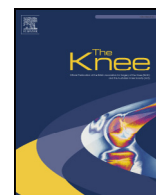
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# Passing return to sports tests after ACL reconstruction is associated with greater likelihood for return to sport but fail to identify second injury risk

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**Background:** A limited number of patients return to sport (RTS) after an anterior cruciate ligament reconstruction (ACLR) and patients who RTS have a relatively high risk for second ACL injury. The purpose of the current study was to compare the results of a test battery between patients who returned to the pre-injury level of sport (RTS group) and patients who did not (NO-RTS group).

It was hypothesized that the RTS group showed better test results.

**Methods:** Sixty-four patients (age  $27.8 \pm 8.8$  years) were included. The results of a multicomponent test battery (jump-landing task assessed with the Landing Error Scoring System (LESS), three hop tests, isokinetic strength test for quadriceps and hamstring) were compared between groups with a  $2 \times 2$  ANOVA.

**Results:** The RTS group showed a significantly lower LESS score ( $p = 0.010$ ), significantly higher absolute scores on hop tests with both legs (injured leg: single leg hop test  $p = 0.013$ , triple leg hop test  $p = 0.024$ , side hop test  $p = 0.021$ ; non-injured leg: single leg hop test  $p = 0.011$ , triple leg hop test  $p = 0.023$ , side hop test  $p = 0.032$ ) and significantly greater hamstring strength in the injured leg ( $p = 0.009$  at  $60^\circ/\text{s}$ ,  $p = 0.012$  at  $180^\circ/\text{s}$  and  $p = 0.013$  at  $300^\circ/\text{s}$ ). No differences in test results were identified between patients who sustained a second ACL injury and patients who did not.

**Conclusion:** Patients after ACLR with better jump-landing patterns, hop performance and greater hamstring strength have greater likelihood for RTS. However, our findings show that RTS criteria fail to identify patients who are at risk for a second ACL injury.

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## 1. Introduction

Return to pre-injury level of sport is often the goal for patients after a reconstruction of the anterior cruciate ligament (ACLR) [1]. After primary ACLR, patient expectations to return to the pre-injury level of sport are high both preoperatively (94%) [2] and

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postoperatively (88%) [3]. For professional athletes, return to sport (RTS) rates to pre-injury level range from 78% to 98% around two years after ACLR [4–6]. Unfortunately, for amateur athletes only 65% of the patients return to their pre-injury level of sport two years after ACLR [7]. The risk for second ACL injury for athletes is relatively high, with the highest rates of second ACL injury in young athletes (up to 23% for patients younger than 25 years) [8]. Additionally, 74% of second ACL injuries occur within the first two years [9,10].

Several factors contribute for RTS after ACLR [11]. Research show that patients with greater muscle strength and higher scores on functional tests are more likely to return to pre-injury level of sport [11–13]. Furthermore, psychological readiness for RTS predicts outcomes one year after ACLR [14]. Therefore, monitoring patient-reported outcome measures (PROMs) seems to be essential for RTS after ACLR [15]. Consequently, multicomponent test batteries are recommended in the RTS readiness decision-making to determine if patients are capable for RTS after ACLR [16,17].

Currently, limited research has been done in the relations of passing RTS criteria, the ability to RTS and the potential risk for second ACL injury. These relations are interesting for clinicians regarding the usefulness of current RTS criteria. Unfortunately, recent evidence shows conflicting results for the relation between RTS criteria and potential risk for second ACL injury [18–24]. One recent systematic review concluded that passing RTS criteria did not result in a decreased risk for second ACL injury [22]. It has been found however that passing RTS criteria reduced the risk of a second ACL injury in the ipsilateral leg by 60%, but increased the risk of a contralateral ACL injury by 235% [23].

The primary purpose of the current study was to compare the results of a test battery at the end of the rehabilitation between patients who returned to the pre-injury level of sport (RTS group) and patients who did not (NO-RTS group) within two years after ACLR. The secondary purpose was to compare the results of the test battery between patients who sustained a second ACL injury and patients who did not. It was hypothesized that the RTS group showed better test results compared to the NO-RTS group. Additionally, it was hypothesized that patients who did not sustain a second ACL injury showed better results compared to patients who sustained a second ACL injury.

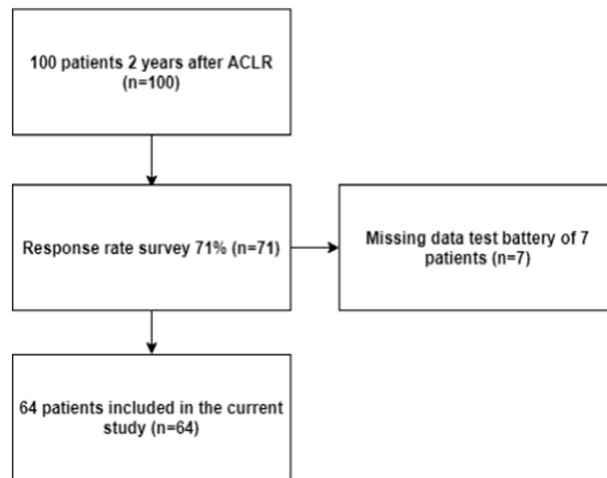
## 2. Methods

For this study, 100 patients after ACLR were identified from an outpatient physical therapy database. All patients were involved in amateur team ball sports (Table 1) and had the ambition to return to the pre-injury level of sport. During their rehabilitation, patients followed the same rehabilitation program. The early phase of the rehabilitation protocol (the first six weeks after ACLR) focused on reducing inflammation and swelling, restoring full knee extension, gait training and neuromuscular training for quadriceps activity. After that, muscle strength and endurance training and more advanced neuromuscular training commences. At 12 weeks, hypertrophy strengthening was started. Additionally, running and jumping exercises were added to the rehabilitation protocol. During the period of 24–44 weeks after ACLR, plyometric activities, running/cutting drills and on field rehabilitation, including sport-specific agility drills were added [16,17]. Inclusion criteria were as follows: 1) participating in competitive, pivoting sports for at least four hours every week, 2) age > 18 years old, 3) primary isolated ACL lesion and 4) arthroscopic ACLR with a hamstring tendon graft or a bone-patellar tendon with an anteromedial portal technique. Patients were excluded if there was 1) a presence of swelling and/or pain of the injured knee during a test moment, 2) no ambition to return to competitive sport or 3) a feeling of instability in the injured knee. Patients performed a multicomponent test battery at the end of the rehabilitation and were followed up to two years after ACLR. Of the patients identified in the database, 71% responded to the invitation to participate in the study, there was missing data of seven patients and therefore, 64 patients were included in the current study (Table 1, Figure 1). All patients signed an informed consent prior to data collection. The study protocol was approved by the Institutional Review Board of the University of Groningen.

**Table 1**  
Descriptive statistics study population for the RTS group and the NO-RTS group.

	RTS, Mean $\pm$ SD	NO-RTS, Mean $\pm$ SD	p-Value
n	46	18	N.A.
Age (years)	25.5 $\pm$ 5.8	33.6 $\pm$ 12.2	0.001*
Gender	33(M), 13(F)	11(M), 7(F)	N.A.
Weight (kg)	74.7 $\pm$ 7.0	76.3 $\pm$ 13.4	0.492
Length (cm)	179.3 $\pm$ 7.0	180.4 $\pm$ 7.2	0.577
Type of graft (n)	HT(29), PT(17)	HT(16), PT(2)	N.A.
Time post surgery at test battery (months)	10.1 $\pm$ 0.9	10.1 $\pm$ 1.0	0.898
Time post surgery questionnaire (months)	24.8 $\pm$ 9.7	25.4 $\pm$ 10.1	0.559
Number of therapy sessions	72.4 $\pm$ 17.1	70.9 $\pm$ 8.8	0.802
Sport	SO(32), HA(6), BA(5), KO(2), VO(1)	SO(15), HA(2), KO(1)	N.A.

\* = significant difference, RTS = patients who returned to the pre-injury level of sport, NO-RTS = patients who did not, M = males, F = females, kg = kilogram, cm = centimeter, HT = hamstring tendon graft, PT = bone-patellar tendon graft, SO = soccer, HA = handball, BA = basketball, KO = korfbal, VO = volleyball. N.A. = not applicable.



**Figure 1.** Flow chart of the included patients in the current study. ACLR = anterior cruciate ligament reconstruction.

### 2.1. Multicomponent test battery (T1)

The test battery was performed at an average of  $10.1 \pm 1.0$  months after ACLR and included the following tests: a jump-landing task assessed with the Landing Error Scoring System (LESS) [25], three hop tests (single leg hop (SLH) test, triple leg hop (TLH) test and side hop (SH) test), isokinetic strength test for quadriceps and hamstring at a velocity of  $60^\circ/\text{s}$ ,  $180^\circ/\text{s}$  and  $300^\circ/\text{s}$  and two questionnaires: the International Knee Documentation Committee Subjective Knee Form (IKDC) to measure self-reported knee function [26] and the Anterior Cruciate Ligament–Return to Sport after Injury (ACL-RSI) [14] to measure psychological readiness for RTS. All tests used were highly reliable (LESS: intraclass correlation coefficient (ICC) = 0.91; SLH: ICC = 0.97; TLH: ICC = 0.80–0.92; SH: ICC = 0.84–0.96; isokinetic device: ICC = 0.91–0.99) [27–30]. The criteria for passing the test battery were: LESS <5 [25], limb symmetry index (LSI) >90% for all three hop tests (SLH, TLH, SH) [16], LSI >90% for isokinetic quadriceps and hamstring strength at  $60^\circ/\text{s}$ ,  $180^\circ/\text{s}$  and  $300^\circ/\text{s}$  [16], quadriceps strength normalized to body weight (BW) >3.0 Nm/kg for the injured leg at  $60^\circ/\text{s}$  [31], hamstring/quadriceps (H/Q) ratio >55% for females and >62.5% for males for the injured leg at  $300^\circ/\text{s}$  [31], ACL-RSI >56 points [14] and IKDC score within 15% of healthy, gender- and age-matched controls [26].

### 2.2. Two years after ACLR (T2)

In the current study, mean follow-up was  $25.1 \pm 9.9$  months after ACLR. A web-based questionnaire was developed by three of the authors (WW, AB, AG) using Google Forms (Google LLC, Mountain View, CA, USA). Data collection took place between December 2017 and April 2018. For data collection, patients were contacted by e-mail and up to two reminders were sent to patients who did not respond after two weeks. Non-responders were contacted by telephone and were asked to participate in the current study. The web-based questionnaire contained the following three questions: “Did you return to the pre-injury level of sport? (yes/no)”, “If not, did you return to a lower level of your pre-injury sport or do you currently perform a different



**Figure 2.** Overview of the study design. ACLR = anterior cruciate ligament reconstruction, T1 = at  $10.1 \pm 1.0$  months after ACLR, T2 = at  $25.1 \pm 9.9$  months after ACLR, LESS = Landing Error Scoring System test, SLH = single leg hop test, TLH = triple leg hop test, SH = side hop test, IKDC = the International Knee Documentation Committee Subjective Knee Form, ACL-RSI = the Anterior Cruciate Ligament–Return to Sport after Injury Scale, IKDC1 = IKDC score at  $10.1 \pm 1.0$  months after ACLR, ACL-RSI1 = ACL-RSI score at  $10.1 \pm 1.0$  months after ACLR, IKDC2 = IKDC score at  $25.1 \pm 9.9$  months after ACLR, ACL-RSI2 = ACL-RSI score at  $25.1 \pm 9.9$  months after ACLR.

sport compared to your pre-injury sport? (open answer)” and “Did you sustain a second ACL injury? (yes/no)”. Furthermore, patients were asked to complete the IKDC and ACL-RSI questionnaires again, which were included within the web-based questionnaire. Figure 2 shows the overview of the study design. The results of the test battery at the end of the rehabilitation were compared between the RTS and the NO-RTS groups.

### 2.3. Data reduction

The LESS test was analyzed by playing frontal and sagittal videos frame by frame [25]. For hop tests and strength tests, LSI values were calculated by dividing the scores of the injured leg by the non-injured leg,  $\times 100$  [17]. Furthermore, absolute values of the quadriceps strength in the injured leg were normalized to BW for the isokinetic peak torque test at 60°/s [31] and H/Q ratios at 300°/s were calculated [32]. Besides the LSI values, all absolute data of the hop tests and strength tests were analyzed. IKDC and ACL-RSI scores were calculated for the two time points (end of rehabilitation and two years after ACLR). Furthermore, the data of the three additional questions was analyzed and groups were created based on the answers.

### 2.4. Statistical analysis

All data was normally distributed as analyzed with SPSS version 20 (IBM SPSS 244 Inc., Chicago, IL). A  $2 \times 2$  ANOVA was conducted to compare the demographic data and the data of the test battery between the RTS group and the NO-RTS groups. In addition, paired sample t-tests were used to investigate the progress in IKDC and ACL-RSI score over time for each group. To analyze the secondary purpose, a  $2 \times 2$  ANOVA was conducted to compare the demographic data and the data of the test battery between patients who sustained a second ACL injury and patients who did not.

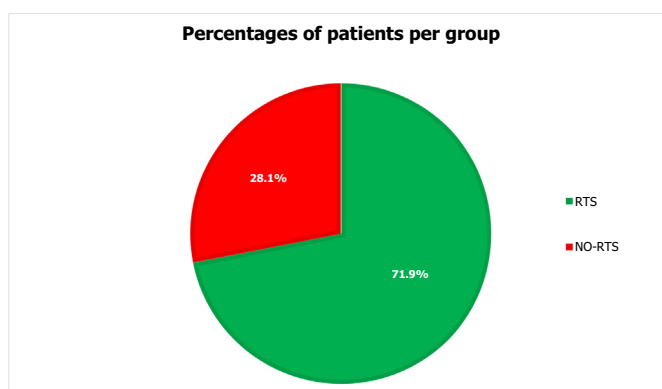
## 3. Results

Two years after ACLR, 71.9% ( $n = 46$ ) were in the RTS group and 28.1% ( $n = 18$ ) were in the NO-RTS group (Figure 3). Patients in the RTS group were significantly younger ( $25.5 \pm 5.8$  years vs.  $33.6 \pm 12.2$  years;  $p = 0.001$ ) compared to patients in the NO-RTS two years after ACLR. For the NO-RTS group, 27.8% ( $n = 5$ ) were active on a lower level in the same sport and 66.7% ( $n = 12$ ) were active in a different sport (non-pivoting sports like running and cycling) two years after ACLR. In addition, one patient was not active in sport at all two years after ACLR.

Patients in the RTS group showed a significantly lower LESS score compared to the NO-RTS group ( $p = 0.010$ ) (Table 2). Although LSI criteria for all hop tests were met ( $LSI > 90\%$ ) for both groups, patients in RTS group had significantly higher absolute scores in both the injured leg and non-injured leg on the SLH, TLH test and the SH test compared to the NO-RTS group (injured leg: SLH  $p = 0.013$ , TLH  $p = 0.024$ , SH  $p = 0.021$ ; non-injured leg: SLH  $p = 0.011$ , TLH  $p = 0.023$ , SH  $p = 0.032$ ) (Table 2). No differences were found in quadriceps strength between patients in the RTS and NO-RTS group. Patients in the RTS group showed significantly greater hamstring strength in the injured leg at 60°/s ( $p = 0.009$ ), at 180°/s ( $p = 0.012$ ) and at 300°/s ( $p = 0.013$ ) and significantly greater LSI values for hamstring strength at 60°/s ( $p = 0.001$ ) and at 180°/s ( $p = 0.012$ ) compared to patients in the NO-RTS group.

Six patients in the RTS group sustained a second ACL injury compared to four patients in the NO-RTS (Table 2). Patients who sustained a second ACL injury were significantly younger ( $21.7 \pm 4.7$  years vs.  $28.9 \pm 9.0$  years;  $p = 0.017$ ) compared to patients who did not. Patients who sustained a second ACL injury did not differ in test results compared to patients who did not sustain a second ACL injury.

The RTS group showed a significantly higher ACL-RSI score compared to the NO-RTS group two years after ACLR ( $p = 0.008$ ) and the RTS group significantly increased their IKDC score over time ( $p < 0.001$ ) (Table 2).



**Figure 3.** Overview of the percentages of patients returned to the returned to the pre-injury level of sport and patients who did not. RTS = patients who returned to the pre-injury level of sport, NO-RTS = patients who did not.

**Table 2**

Results of the test battery for the RTS group and the NO-RTS group.

	RTS (Mean $\pm$ SD)	NO-RTS (Mean $\pm$ SD)	p-Value
Second ACL injury (n)	6 (13.0%)	4 (22.2%)	N.A.
Ipsilateral/contralateral (n)	5/1	3/1	N.A.
Passing all RTS criteria (n)	6 (13.0%)	1 (5.6%)	N.A.
LESS	3.1 $\pm$ 1.4	4.4 $\pm$ 2.5	0.010*
SLH injured leg (cm)	163.7 $\pm$ 27.4	142.4 $\pm$ 35.6	0.013*
SLH non-injured leg (cm)	168.8 $\pm$ 25.6	149.4 $\pm$ 29.5	0.011*
LSI SLH (%)	97.1 $\pm$ 8.4	95.0 $\pm$ 13.4	0.445
TLH injured leg (cm)	524.8 $\pm$ 84.4	469.3 $\pm$ 91.5	0.024*
TLH non-injured leg (cm)	538.9 $\pm$ 81.2	487.4 $\pm$ 75.2	0.023*
LSI TLH (%)	97.4 $\pm$ 6.4	96.1 $\pm$ 9.7	0.509
SH injured leg (number)	53.3 $\pm$ 13.1	43.8 $\pm$ 17.1	0.021*
SH non-injured leg (number)	54.4 $\pm$ 11.6	46.9 $\pm$ 14.0	0.032*
LSI SH (%)	98.0 $\pm$ 14.1	91.3 $\pm$ 17.1	0.116
Quadriceps strength 60°/s injured leg (Nm)	223.9 $\pm$ 51.2	208.0 $\pm$ 42.6	0.246
Quadriceps strength 60°/s non-injured leg (Nm)	239.3 $\pm$ 53.6	223.4 $\pm$ 45.0	0.272
LSI quadriceps strength 60°/s (%)	93.9 $\pm$ 9.2	93.5 $\pm$ 9.2	0.869
Hamstring strength 60°/s injured leg (Nm)	136.8 $\pm$ 31.9	113.1 $\pm$ 31.4	0.009*
Hamstring strength 60°/s non-injured leg (Nm)	137.0 $\pm$ 31.7	125.1 $\pm$ 36.6	0.203
LSI hamstring strength 60°/s (%)	100.1 $\pm$ 9.8	91.3 $\pm$ 8.7	0.001*
Quadriceps strength 180°/s injured leg (Nm)	158.2 $\pm$ 37.4	146.7 $\pm$ 34.7	0.266
Quadriceps strength 180°/s non-injured leg (Nm)	167.4 $\pm$ 37.2	155.2 $\pm$ 34.0	0.230
LSI quadriceps strength 180°/s (%)	94.7 $\pm$ 9.1	89.6 $\pm$ 24.8	0.186
Hamstring strength 180°/s injured leg (Nm)	107.9 $\pm$ 25.2	89.9 $\pm$ 24.8	0.012*
Hamstring strength 180°/s non-injured leg (Nm)	109.3 $\pm$ 23.8	98.4 $\pm$ 27.3	0.119
LSI hamstring strength 180°/s (%)	98.7 $\pm$ 9.7	91.7 $\pm$ 9.5	0.012*
Quadriceps strength 300°/s injured leg (Nm)	121.3 $\pm$ 30.2	112.2 $\pm$ 30.6	0.286
Quadriceps strength 300°/s non-injured leg (Nm)	129.5 $\pm$ 30.5	120.1 $\pm$ 30.1	0.271
LSI quadriceps strength 300°/s (%)	93.7 $\pm$ 0.8.7	93.7 $\pm$ 9.1	0.979
Hamstring strength 300°/s injured leg (Nm)	91.4 $\pm$ 21.3	76.3 $\pm$ 21.4	0.013*
Hamstring strength 300°/s non-injured leg (Nm)	91.4 $\pm$ 20.4	80.7 $\pm$ 22.2	0.071
LSI hamstring strength 300°/s (%)	100.1 $\pm$ 9.4	94.8 $\pm$ 10.4	0.057
Quadriceps peak torque at 60°/s normalized to BW (Nm/kg)	3.0 $\pm$ 0.6	2.8 $\pm$ 0.5	0.124
H/Q ratio at 300°/s	0.8 $\pm$ 0.2	0.7 $\pm$ 0.2	0.179
IKDC1	82.3 $\pm$ 7.2	85.6 $\pm$ 8.4	0.387
ACL-RSI1	71.5 $\pm$ 17.7	69.5 $\pm$ 20.1	0.697
IKDC2	91.5 $\pm$ 7.6	89.6 $\pm$ 8.1	0.375
ACL-RSI2	78.7 $\pm$ 19.7	62.6 $\pm$ 24.4	0.008*

\* = significant difference, RTS = patients who returned to the pre-injury level of sport, NO-RTS = patients who did not, ACL = anterior cruciate ligament, N.A. = not applicable, \* = significant difference, Nm = newton meter, LSI = limb symmetry index, kg = kilogram, H/Q = hamstring/quadriceps, SLH = single leg hop test, TLH = triple leg hop test, SH = side hop test, cm = centimeter, LESS = Landing Error Scoring System test, IKDC = the International Knee Documentation Committee Subjective Knee Form, ACL-RSI = the Anterior Cruciate Ligament–Return to Sport after Injury Scale, IKDC1 = IKDC score at 10.1  $\pm$  1.0 months after ACLR, ACL-RSI1 = ACL-RSI score at 10.1  $\pm$  1.0 months after ACLR, IKDC2 = IKDC score at 25.1  $\pm$  9.9 months after ACLR, ACL-RSI2 = ACL-RSI score at 25.1  $\pm$  9.9 months after ACLR.

#### 4. Discussion

The primary findings of the current study were that a lower LESS score, higher absolute scores on hop tests and greater hamstrings strength result in higher RTS rates to pre-injury level two years after ACLR. Passing or not passing the RTS criteria was not correlated with second ACL injury, indicating that RTS criteria used in this study fail in identifying patients who are at risk for a second ACL injury.

In the current study, around 70% of the patients returned to the pre-injury level of sport two years after ACLR which is comparable to previous reported 65% RTS rates [7,12]. Patients in the RTS group were younger compared to patients in the NO-RTS group which indicates that younger patients have increased likelihood to return to pre-injury level of sport after ACLR. This is in line with earlier studies linking younger age with increased RTS rates [7,33–36].

Overall, around 15% of patients sustained a second ACL injury within two years after ACLR, which is similar to earlier reported studies [37,38]. Furthermore, our results showed that patients who sustained a second ACL injury were younger compared to patients who did not. Similar findings were found in earlier studies, showing that younger age results in higher rates for second ACL injury [7,37,39]. Although no information was collected about the patients' athletic exposures and/or level of exposures, these results are logical since patients in the RTS group were also younger compared to patients in the NO-RTS group. Therefore, these younger patients have increased risk for a second ACL injury since returning to a pivoting sport is more demanding compared to a non-pivoting sport [40].



#### 4.1. Multicomponent test battery (T1)

Only seven patients (10.9%) passed all RTS criteria which is comparable with previous research, showing that low rates of patients meeting RTS criteria after ACLR [16,17,23,41,42]. This raises the question regarding the usefulness of current RTS criteria, since the majority of the patients fail in passing RTS criteria. On the other hand, 85% of the patients who passed all RTS criteria, returned to the pre-injury level of sport. The problem with a large array of RTS criteria is that the overall pass rate for the test battery is dependent on the total number of tests and cut-off criteria [23]. The more tests and criteria included, the more difficult it is for patients to pass all criteria. For example, the study of Grindem et al. [19] used seven criteria (compared to 14 criteria the current study), resulting in a 24% pass rate compared to 11% in the current study. For patients in the current study, passing all criteria of the test battery is almost utopian. The current study is part of an ongoing project which started in 2017 with the development of a RTS test battery for patients after ACLR [16]. Since low percentages of patients passed RTS criteria at both six [16] and nine months after ACLR [17], the current RTS criteria might be revised and potentially limited. For example, in the current study eight criteria were used related to muscle strength compared to only one criterion in the study of Grindem et al. [19], using only LSI >90% for quadriceps strength at 60°/sec besides LSI >90% for four hop tests and two questionnaires. If we use these criteria for the patient population in the current study, 54.7% ( $n = 35$ ) of patients would have passed the RTS criteria. These findings indicate that the number of tests used in the current study might need revision. In addition, no differences were found in quadriceps strength between the RTS and the NO-RTS group. Furthermore, no differences in quadriceps strength were found between patients who sustained a second ACL injury and patients who did not. These findings are in conflict with earlier studies showing the importance of quadriceps strength in the reduction of a second ACL injury [18,19]. For example, the study of Grindem et al. [19] found that patients who sustained a second ACL injury had a lower LSI value for quadriceps strength compared to patients who did not. Although the same isokinetic test was used for quadriceps strength, the percentage of included female patients was higher compared to the current study population (54% in [19] compared to 31% in the current study). This might explain the conflicting results. Furthermore, this study did not present absolute quadriceps strength values (only LSI values), which makes it hard to compare with the results in the current study [19].

The results of the test battery indicate that better jump-landing patterns at the end of the rehabilitation result in higher RTS rates. Therefore, clinicians are encouraged to analyze movement quality including jump-landing patterns before RTS [43]. Less optimal movement quality during functional movements could potentially increase the risk for second ACL injury [44,45]. However, in the current study no differences in jump-landing patterns were found between patients who sustained a second ACL injury and patients who did not. This indicates that the drop vertical jump (assessed with the LESS) is a poor test to identify second ACL injury risk [46]. However, this is in conflict with earlier findings, showing that altered movements in hip and knee (for example more knee valgus displacement) during a dynamic landing task was correlated with a second ACL injury in young athletes [47]. One potential reason for these conflicting results might be related to the 3D motion analysis system used in the study of Paterno and colleagues [47]. Furthermore, the study population used in [47] was significantly younger ( $16.4 \pm 3.0$  vs.  $27.8 \pm 8.8$  years in the current study). These differences might explain the conflicting results in the relation between altered jump-landing patterns and increased risk for second ACL injury.

No differences were found in LSI values on all three hop tests (SLH test, TLH test and SH test) between groups. However, when comparing the absolute scores the RTS group jumped further in the SLH and in the TLH test and scored higher on the SH test with both legs compared to the NO-RTS group. The results of the current study are similar compared to previous research demonstrating greater absolute functional performance on single leg hop test in patients who returned to the pre-injury level of sport after ACLR [24]. Although patients in Ithurburn et al. [24] were younger ( $17.1 \pm 2.4$  years in Ithurburn et al. [24] compared to  $27.8 \pm 8.8$  years in the current study) and more female patients were included compared to the current study (75% female patients in Ithurburn et al. [24] compared to 31% in the current study), both the study of Ithurburn et al. [24] and the current study indicate that underlying, overall athleticism may contribute to RTS. Furthermore, these findings show that only using LSI values for the RTS decision making can mask bilateral deficits and overestimate performance [16,17,48,49]. Therefore, the use of LSI values could give clinicians incomplete information about the patients' performance [48]. In addition, leg dominance is suggested to affect LSI values [49] since the dominant leg is often stronger than the non-dominant leg [50]. Clinicians are encouraged to use absolute norm values instead of only LSI values to determine RTS readiness [48,49].

The current study used a standardized rehabilitation program. Interestingly, a recent study [50] found that using more progressive strength training within ACLR rehabilitation results in increased quadriceps strength normalized to BW in the injured leg compared to a standardized rehabilitation ( $3.2 \pm 0.6$  Nm/kg with a passing rate of 71.1% for  $>3.0$  Nm/kg in [50] compared to  $2.9 \pm 0.6$  Nm/kg with a passing rate of only 46.9% in the current study). This raises the question if the quality of rehabilitation in the current study was sufficient enough for patients to RTS. Increasing the quality of the ACLR rehabilitation by implementing more progressive strength training results in higher passing rates for RTS strength criteria [50] which potentially increase RTS rates and decrease the risk for second ACL injury. Future research should focus on longitudinal follow up studies after implementing progressive strength training within rehabilitation.

Patients in the RTS group showed greater hamstring strength compared to patients in the NO-RTS. In addition, the RTS group showed more symmetrical hamstring strength. This is in line with earlier findings, showing more symmetrical hamstring strength in patients who successfully resumed pre-injury sports participation compared to patients who did not [24]. On the other hand, no differences in hamstring strength were found between patients who sustained a second ACL injury and patients who did not. However, decreased hamstring strength is suggested to be a contributing mechanism to ACL injuries, especially in female athletes [51]. Instead of measuring absolute hamstring strength values and symmetry, the H/Q ratio might be a more relevant variable for

investigating risk for second ACL injury [18]. In the current study, H/Q ratios at 300°/s were used as RTS criteria. However, H/Q ratios at 60°/s might be more relevant since Kyritsis and colleagues found a 10 times greater risk for every 10% difference in H/Q ratio at 60°/s [18]. Comparable values were found for H/Q ratios at 60°/s in the current study between patients who sustained a second ACL injury and patients who did not ( $53.8 \pm 9.5$  vs.  $61.1 \pm 12.5\%$  in the current study compared to  $53 \pm 11$  vs.  $58 \pm 10\%$  in [18]), indicating that a decreased H/Q ratio at 60°/s might be correlated with risk for second ACL injury. Many studies in the area of ACL injuries are focused on achieving quadriceps strength [12,52–54] but the results of the current study also highlight the importance of hamstring strength.

Patients who sustained a second ACL injury did not differ in test battery results compared patients who did not. This is in line with the evidence showing a poor relation between passing RTS criteria and decreased risk for second ACL injury [18–22]. This raises the question on what the best clinical factors are to evaluate risk for second ACL injury [24]. In addition, a recent systematic review questioned if current test batteries are valid instruments to determine the risk for second ACL injury [23]. Our findings suggest that current test batteries can be used to determine the likelihood that patients resume sports at pre-injury level, but fail in identifying patients who are at risk for a second ACL injury. Furthermore, our findings show that younger patients have increased risk for a second ACL injury since younger patients are more likely to return to the pre-injury level of a pivoting sport compared to older patients who are more likely to do a less demanding non-pivoting sport [40].

#### 4.2. PROMs two years after ACLR (T2)

Psychological readiness for RTS is essential for RTS after ACLR since this is a predictor for returning to pre-injury level of sport in amateur athletes [14,15]. The findings of the current study are in agreement with previous research showing that patients in the RTS group showed higher psychological readiness for RTS two years after ACLR compared to patients in the NO-RTS. It is suggested that clinicians can influence both the physical and psychological recovery of an athlete [37]. Therefore, psychological readiness for RTS should be monitored during rehabilitation, and if needed, targeted interventions should be used to increase psychological factors [43]. Our results showed that only patients in the RTS group demonstrated a clinically relevant improvement of the IKDC score. More in detail, the absolute increase in IKDC score of patients in the RTS group was 9.2 which is similar to the minimal detectable change of 8.8 [55]. Self-reported knee function and psychological readiness should be monitored after the rehabilitation since this can significantly influence RTS rates.

### 5. Limitations

A number of potential study limitations should be noted. There is a risk for response bias, since the response rate of the current study was 71%. Additionally, the questionnaire was conducted at an average of 25.1 months after ACLR, with a standard deviation of 9.9 months. This relatively high standard deviation could influence the results significantly. In the current study, the potential effects of different athlete exposures and/or level of exposures were not investigated. Also, defining groups (RTS vs. NO-RTS) was based on the results of a questionnaire and it was unknown if patients actually returned to the pre-injury level of sport. Future research should focus on measuring RTS, in terms of games played, scoring and career length in amateur athletes after ACLR [56,57]. Furthermore, patients were tested at  $10.1 \pm 1.0$  months after ACLR and it was unknown if and what kind of training patients did after rehabilitation. In other words, it is unknown how strength or hop performance developed over time. Measuring patients at one moment in time and comparing the test results with their performance two years later, might be methodological flawed. Therefore, future research should focus on repeated measurements over time in patients after ACLR. Also, LSI values were used in the current study which could result in incomplete information about the patients' performance. In the current study, it was unknown if all second ACL injuries were non-contact injuries. Last, future research should consider patients as complex biological systems, without direct relations between isolated factors (strength, hop performance, jump-landing patterns, PROMs) and the outcome (RTS) [58].

### 6. Conclusion

Better jump-landing patterns, improved hop performance and greater hamstring strength result in greater likelihood for RTS in patients after ACLR. These findings can help clinicians to identify patients who are more likely to RTS. Of caution, current RTS criteria fail in identifying patients who are at risk for a second ACL injury.

#### Conflict of interest

The authors have declared no conflict of interest.

#### Ethical approval

The study was approved by the Review Board at the University of Groningen.



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